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© 2020 Tongji University The reliability of disc cutters has a significant influence on the safety and working efficiency of tunnel boring machines (TBMs). To investigate the reliability of disc cutters under different geological and operational conditions, we conducted a series of novel rolling cutting tests on intact and jointed sandstone blocks using different dip angles and interlayers. Different normal forces and rotational speeds of the cutterhead were also applied during the experiment. A novel reliability estimation method, based on a logistic regression model, was then proposed, and the influence of dip angle, strata, normal force, and rotational speed on the reliability of the disc cutter were analyzed. The reliability estimation method consisted of data acquisition regarding the normal force and cutter wear, feature extraction using wavelet packet transform and correlation analysis, and the estimation of the logistic regression model. To obtain the spectrum and normalized wavelet energy for each frequency band, we decomposed the time domain of the normal force by the wavelet packet transform. A correlation analysis was employed to determine the feature frequency bands that were sensitive to wear loss. On the basis of salient feature parameters and wear loss, the logistic regression model was established to evaluate the reliability of disc cutters. The analytical results indicated that the optimal dip angle for rock cutting was 30°. In the presence of mixed-face and single ground, the reliability of disc cutters was primarily affected by the difficulty of TBM excavation and wear loss, respectively. An increase in normal force and rotational speed aggravated wear on the cutter, thus reducing reliability. Furthermore, compared to Rabinowicz's formula, the proposed method considers various geological and operational conditions, making the proposed method more applicable to estimate the reliability of disc cutters.

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Reliability analysis of TBM disc cutters under different conditions

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Abstract

The reliability of disc cutters has a significant influence on the safety and working efficiency of tunnel boring machines (TBMs). To investigate the reliability of disc cutters under different geological and operational conditions, we conducted a series of novel rolling cutting tests on intact and jointed sandstone blocks using different dip angles and interlayers. Different normal forces and rotational speeds of the cutterhead were also applied during the experiment. A novel reliability estimation method, based on a logistic regression model, was then proposed, and the influence of dip angle, strata, normal force, and rotational speed on the reliability of the disc cutter were analyzed. The reliability estimation method consisted of data acquisition regarding the normal force and cutter wear, feature extraction using wavelet packet transform and correlation analysis, and the estimation of the logistic regression model. To obtain the spectrum and normalized wavelet energy for each frequency band, we decomposed the time domain of the normal force by the wavelet packet transform. A correlation analysis was employed to determine the feature frequency bands that were sensitive to wear loss. On the basis of salient feature parameters and wear loss, the logistic regression model was established to evaluate the reliability of disc cutters. The analytical results indicated that the optimal dip angle for rock cutting was 30°. In the presence of mixed-face and single ground, the reliability of disc cutters was primarily affected by the difficulty of TBM excavation and wear loss, respectively. An increase in normal force and rotational speed aggravated wear on the cutter, thus reducing reliability. Furthermore, compared to Rabinowicz's formula, the proposed method considers various geological and operational conditions, making the proposed method more applicable to estimate the reliability of disc cutters.

Keywords: Tunnel boring machine; Sandstone; Disc cutter reliability; Logistic regression model

1 Introduction

Disc cutters are essential components in tunnel boring machines (TBMs), and therefore, significantly influence the boring performance of TBMs (Cardu, Iabichino, Oreste, & Rispoli, 2017; Jeong, Cho, Jeon, & Rostami, 2016; Yang, Liu, & Liu, 2018; Yang, Wang, & Zhou, 2016). During the rock cutting process, disc cutters roll on the surface of a rock mass and gradually wear under the action of thrust and torque. In TBM tunneling projects, replacing worn cutters significantly reduces the TBM utilization and advance rate, causing an increase in project cost and downtime (Liu et al., 2017; Roby, Sandell, Kocab, & Lindbergh, 2008). Wear extent varies significantly in different geological conditions (Liu, Yang, & Karekal, 2019; Zhao et al., 2019). Therefore, accurately predicting the cutter wear and analyzing the reliability of disc cutters is essential to avoid budget overruns and improve the work efficiency of TBMs.

Many prediction models for cutter wear have been established to date. Based on experimental research, some classical models were proposed to predict cutter wear. The Colorado School of Mines model (Hassanpour, Vanani, Rostami, & Cheshomi, 2016) is one of globally employed models, in which the Cerchar abrasivity index is used to predict cutter consumption and the time spent on replacing worn cutters. However, some new prediction

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methods were proposed, based on field data obtained from tunneling projects. For example, Zare and Bruland (2013) estimated wear values using the Norwegian University of Science and Technology model; the cutter life index (CLI) obtained from Sievers' J-value and the abrasion value tests are important indexes in the model. Factors influencing the cutter wear include TBM diameter, cutter diameter, CLI, and rock quartz content. Wang et al. (2012) proposed a specific energy rule and studied the wear mechanism of TBMs, from which a new energy method was established to predict disc cutter wear extent. This model was subsequently applied to Qinling tunnel boring project to demonstrate its applicability. Hassanpour, Rostami, Azali, and Zhao (2014) also proposed a new empirical model to predict cutter wear, based on field data from a long tunnel in Iran; the model is applicable to the condition of pyroclastic and mafic igneous rocks. Zhang, Meng, and Sun (2014) defined a comprehensive radial wear coefficient, comprehensive axial wear coefficient, and comprehensive trajectory wear coefficient to analysis cutter wear. The calculation and determination of wear coefficients was based on data from a segment of the TBM project. The wear coefficients were then employed to predict disc wear in the follow-up segment of the TBM project. Recently, in order to adapt rapid development of the TBM technology, Liu et al. (2017) studied the wear rule of a 20-inch disc cutter. Subsequently, a new empirical model was proposed to predict the cutter life in a water conveyance tunnel project in China. However, the classical prediction models mentioned above were proposed based on the Cerchar scratch test, Sievers' J-value, and the AVS tests. The abrasion mode of the cutter differs in practice and experimental results are affected by test conditions. Therefore, in these prediction models, the rock cutting processes of TBMs cannot be realistically simulated. Moreover, new prediction models based on field data are not always suitable for other tunnel projects. Thus, the applicability needs to be further developed.

Reliability assessments and performance predictions are longstanding research topics in geotechnical engineering (Camós, Špačková, Straub, & Molins, 2016; Gravanis, Pantelidis, & Griffiths, 2014; Shin, Kwon, Jung, Bae, & Kim, 2009; Xiang et al., 2018; Zhang & Goh, 2012; Zhang, Wu, Li, Wang, Samui, 2019; Zhang, Zhang, et al., 2019). Reliability indicates the ability of tools to achieve their goals in a given time, which is related to tool life. In the rock breaking process of a TBM, the reliability of disc cutters varies greatly in different projects, owing to the complexity of geological conditions. Sun and Li (2017) first presented a probabilistic risk assessment approach to estimate the failure risk of cutting tools. The approach considers many factors, such as the properties of the rock and cutting tools. Considering the benefits of improving tool life and reliability of cutter tools, relevant studies have also been conducted in mechanical engineering. Wang, Lin, and Hsu (2001) presented a reliability-dependent failure rate model, based on reliability theory, to predict the reliability of a cutting tool, under the condition of flank wear. Ding and He (2011) analyzed the operational reliability of cutting tools by a proportional hazards model, proposing a different approach to Klim, Ennajimi, Balazinski, and Fortin (1996) and Wang et al. (2001). The root mean square and peak of the time domain index were employed in this model. Salonitis and Kolios (2014) proposed novel reliability estimation methods, based on stochastic response surface and surrogate modeling methods, Monte Carlo simulations, and first- and second-order reliability methods. Additionally, Sun, Zhang, and Niu (2016) proposed a method to evaluate the remaining useful life of an individual cutting tool, according to the operational reliability. Despite the importance of assessing the reliability of cutters in tunneling engineering, limited work has been conducted in this field. Other influencing factors, such as geological conditions (intact rock parameters, rock mass parameters) and TBM operational parameters (cutterhead trust, rotational speed) are still poorly understood.

In the present study, a series of novel rolling cutting tests were conducted on intact rocks and rock blocks using different dip angles and strata. A reliability estimation model, developed by Chen et al. (2011), was introduced to analyze the reliability of disc cutters. The analysis process included data acquisition, features extraction by wavelet packet (WP) transform and correlation analysis, the estimation of a logistic regression model, and a reliability estimation. The influence of various parameters such as dip angle, penetration depth, and the strength of interlayer on the reliability of disc cutters is discussed. Although the basic calculation method in this study is similar to that proposed by Chen et al. (2011), this model is employed to estimate the reliability of disc cutters in tunnel engineering for the first time.

2 Experimental methodology

2.1 Rock blocks preparation and test device

As a typical rock type encountered in tunnel construction, sandstone was used in the rolling cutting experiment. The experiment required sandstone specimens appropriate for the size of the miniature TBM and the cracking process of the specimens; therefore, the sandstone was cut into intact rock blocks with dimensions of 160 mm × 160 mm × 100 mm to eliminate the edge effect (Fig. 1(a)). Intact rock blocks were further cut into slices with a fixed joint spacing of 20 mm for simulating a jointed rock mass. Dip angles α between the horizontal plane and joint plane were set to 0°, 30°, 45°, 60°, and 90° (Fig. 1(b)). In addition, rock blocks with three types of interlayers were prepared to model different mixed-face grounds. The layered rock blocks comprised of main rock (sandstone) and interlayers. Interlayers can be classified into three groups, categorized by the uniaxial compressive strength of the material, namely hard interlayer (gypsum), medium hard interlayer (silty mudstone, which is made of clay, river sand, and gyp-

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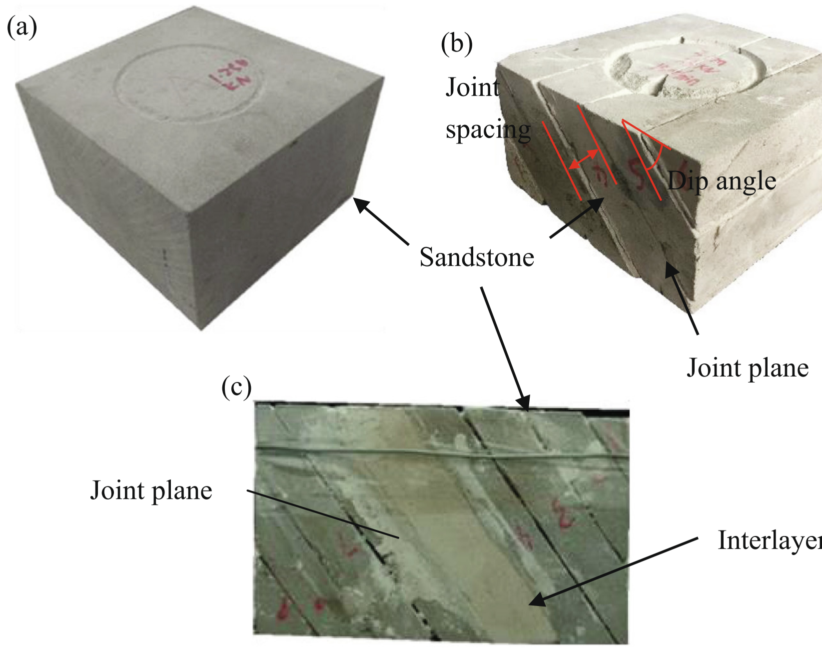

Fig. 1. The rolling cutting experiment of rock blocks for (a) intact rock blocks, (b) Rock blocks with different dip angles, and (c) rock blocks with different interlayers.

sum, with a mass ratio of 5:5:2), and soft interlayer (fine-sandy mudstone, which is made of clay, river sand, and gypsum, with a mass ratio of 4:2:1). The joint spacing and dip angle of the layered rock blocks were 20 mm and 45°, respectively, as shown in Fig. 1(c). The physical and mechanical properties of the rock samples are listed in Table 1.

2.2 Experimental device and procedure

As shown in Fig. 2, the testing system primarily consisted of the loading system, data acquisition system, and a self-designed TBM. Specifically, the loading system contained an MTS servo-hydraulic universal machine, which was employed to apply a normal force on the reduced scale TBM. The data acquisition system consisted of a computer and force and displacement sensors. The TBM primarily comprised of two miniature disc cutters, an M-type miniature cutterhead, a bearing, a pair of gears, and a motor. The disc cutters were made of H13 steel with a Rockwell hardness of 45 ± 1. Moreover, a miniature disc cutter, with a diameter of 70 mm, was used to simulate disc cutters in a real engineering environment, which had a diameter range from 381 to 483 mm. Thus, the geometric similarity ratio varied from 5.4 to 6.9. In the experiment, the value was set to 6.5. The spacing between the cutters was 80 mm. A detailed design of the disc cutters is depicted in Fig. 3. Similar to the rolling indentation abrasion test proposed by

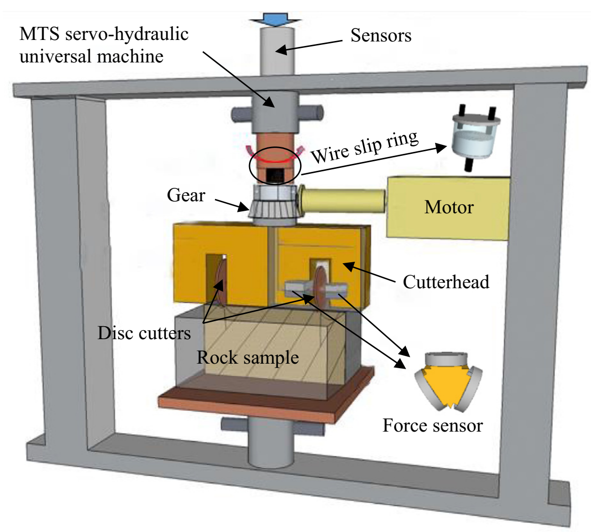

Fig. 2. Schematic diagram of the experimental device, including the loading system, data acquisition system, and self-designed TBM.

Table 1
Physical and mechanical properties of the rock samples.

Rock types	Density (kg/m^3)	Elastic model (GPa)	Uniaxial compressive strength (MPa)	Tensile strength (MPa)	Poisson ratio
Sandstone	2400	28.64	30.0	2.0	0.2
Gypsum	2610	3.82	27.5	0.63	0.2
Silty mudstone	2000	1.79	4.3	0.41	0.3
Fine-sandy mudstone	2000	1.76	3.5	0.39	0.3

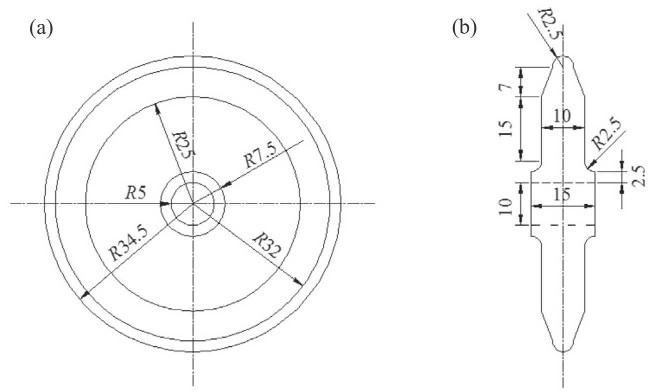

Fig. 3. Size of disc cutters in mm. (a) Front view, (b) Side view.

Macias, Dahl, and Bruland (2016), in this experiment, three load cells were installed on both ends of the axis to measure the normal and rolling forces acting on the disc cutters. The cutterhead was driven by a motor through a pair of gears. A wire slip ring was installed in the upper part of the seamless steel pipe for the convenience of rotating the sensors.

During the experiment, the self-designed TBM and motor were first fixed on the MTS servo-hydraulic universal machine, which applied a normal force on the cutterhead. To alleviate the boundary effect that was produced in the rock breaking process, we installed four angle steels around the specimen to simulate the natural, confining, pressured environment. The disc cutters rolled on the surface of the rock blocks, driven by a motor with an adjustable speed. The normal force, rolling force, and penetration depth of the disc cutters were recorded in real time. Furthermore, the mass of the disc cutters was recorded before and after the experiments to obtain their wear values. When the torque acting on the cutterhead exceeded the power of the motor, the experiment was terminated.

On the basis of engineering practice, stress in the contact area of an actual TBM cutter is about 300 MPa and cutter rolling velocity changes from 1.4 to 2.9 m/s. To simulate a realistic rock breaking process of a TBM, we controlled the normal force acting on the cutterhead at 1.5 kN and the rotational speed of the cutterhead was set at 15 r/min.

The experiment was divided into four groups to investigate the effects of geological and operational conditions on the reliability of disc cutters. Rock blocks with different dip angles (Group 1), interlayers (Group 2), normal forces (Group 3), and rotational speeds (Group 4) were subjected to rolling cutting tests. The experimental parameters are listed in Table 2.

3 Reliability estimation for disc cutters based on logistic regression model

Logistic regression is a widely employed method for calculating the failure probability of facilities based on multiple variables. This approach does not rely on normality assumptions of variables or errors, and the selection effect could vary nonlinearly (Janzen & Stern, 1998). To estimate the reliability of disc cutters during tunneling, we employ a logistic regression model proposed by Chen et al. (2011). The analysis process is primarily divided into three steps: (i) Data acquisition on the normal force and cutter wear; (ii) Features extraction by WP transform and correlation analysis; (iii) Estimation of the logistic regression model and reliability. Among the different categories of tests, the test performed on an intact rock block with a normal force of 1.5 kN is used as an example to illustrate the calculation process.

3.1 Data acquisition on the normal force and cutter wear

In this experiment, as the TBM rolled on rock blocks, the normal force acting on the cutterhead was recorded in real time. The variation of the normal force with time is shown in Fig. 4. The mass loss of the disc cutter was 12 mg. A distinct change in the normal force was observed at approximately 1.5 kN, indicating that the cutterhead dramatically vibrated during the tunneling. However, the time domain of the normal force cannot reflect any information about wear loss; thus, the reliability of the cutter cannot be estimated. To address this shortcoming, spectral analysis is necessarily performed to decompose the time domain of the normal force into its spectrum.

Table 2
Experimental parameters of rock samples in each group.

Group order	Rock blocks	Rock types	Joint spacing (mm)	Dip angle (°)	Rotational speed (r/min)	Normal force (kN)
1	Jointed rock block	Sandstone	20	0, 30, 45, 60, 90	15	1.5
2	Layered rock blocks	Sandstone and gypsum, sandstone and silty mudstone, sandstone and fine-sandy mudstone	20	45	15	1.5
3	Intact rock block	Sandstone	—	—	15	1.00, 1.25, 1.50, 1.75, 2.00
4	Jointed rock block	Sandstone	20	45	5, 10, 15, 20, 25	1.5

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3.2 Features extraction by WP transform and correlation analysis

For the purpose of determining the significant factors that influence wear loss, the salient features indicative to cutter wear should be extracted, based on the time domain of the normal force. As mentioned above, spectral analysis was performed after the experiment. In this study, the WP transform was used in the spectral analysis process. Thus, energy and time domain feature parameters of each frequency band and energy entropy could be obtained. Subsequently, correlation analysis was performed to determine the feature bands sensitive to wear loss. As a result, salient feature parameters, which may consist of feature band energy, energy entropy, and time domain parameters of feature bands, were extracted.

3.2.1 Introduction of WP transform

The WP transform is a useful spectral analysis method for decomposing the vibration signal. As stated by Chen et al. (2011), when the signal is decomposed by an n-level wavelet packet, 2^n nodes would appear in the n^{th} floor. Each node can be represented by (x, y), where x is the number of the floor and y is the node number in each floor. The iteration formula can be expressed as

$$V_{j+1}^{n} = V_j^{2n} \oplus W_j^{2n+1}, \quad j \in \mathbf{Z}, \ n \in \mathbf{Z}_+, \tag{1}$$

where j ($j < 0$) is the resolution level, $\oplus$ represents orthogonal decomposition, $\mathbf{Z}$ denotes the integer domain, $\mathbf{Z}_+$ is the positive integer domain, and V_{j+1}^{n}, V_j^{2n}, and W_j^{2n+1} are closure spaces. The corresponding WP functions are $\psi_n(t)$, $\psi_{2n}(t)$, and $\psi_{2n+1}(t)$, which represent the two-scaled equations, as given below:

$$\begin{cases} \psi_{2n}(t) = \sqrt{2}\sum\limits_{k\in\mathbf{Z}} h(k)\psi_n(2t-k), \\ \psi_{2n+1}(t) = \sqrt{2}\sum\limits_{k\in\mathbf{Z}} g(k)\psi_n(2t-k), \end{cases} \tag{2}$$

where $h(k)$ and $g(k)$ are discrete coefficients of the quadrature mirror filter.

The sub-signal at V_j^{n-1} can be reconstructed by the WP function $\psi_k^{j,n}(t)$:

$$s_j^n(t) = \sum_{k\in\mathbf{Z}} D_k^{j,n}\psi_k^{j,n}(t), \quad k \in \mathbf{Z}, \tag{3}$$

where $s_j^n(t)$ is the sub-signal at V_j^{n-1}, the n^{th} subspace on the j^{th} level. $D_k^{j,n}$ is the WP coefficient, which can be obtained from

$$D_k^{j,n} = \int_{-\infty}^{+\infty} f(t)\psi_k^{j,n}(t)\mathrm{d}t. \tag{4}$$

Because $\psi_k^{j,n}(t)$ is an orthogonal basis function, the energy of $s_j^n(t)$ can be expressed as

$$E_n = \sum_k \left|D_k^{j,n}\right|^2, \tag{5}$$

where E_n represents the energy of $s_j^n(t)$.

The normalized wavelet energy is expressed as

$$E = E_n / \sum_n E_n, \tag{6}$$

where E is the normalized wavelet energy, $\sum\limits_n E_n$ is the energy in the entire scaling space.

The wavelet energy entropy reflects the change of wavelet energy of different frequency bands, which is defined as

$$I = -\sum_n E_n \ln E_n. \tag{7}$$

According to Eqs. (1)–(6), the variations of the normal force with time are decomposed into four layered wavelet packets, using a threshold wavelet of 10 dB. By normalizing the energy, the energy spectra of 16 frequency bands were then obtained. Figure 5 shows the normalized wavelet energy spectrum of the intact rock block with a normal force of 1.5 kN at 15 min. It can be observed that the energy was primarily focused on band interval 1–3 for this moment.

3.2.2 The time domain feature parameters

During the rock cutting process, the signal characteristics of cutters, such as vibration amplitude and vibration period, changed as the disc cutter varied from sharp to worn. Silva, Reuben, Baker, and Wilcox (1998) suggested that some time domain feature parameters can reflect tool wear. Therefore, to obtain more parameters sensitive to wear change, we extracted a total of 11 time-dominant feature parameters of the normal force of each frequency band: mean (x_{m}), peak (x_{p}), root amplitude (x_{ra}), root mean square (x_{rms}), standard deviation (x_{std}), skewness

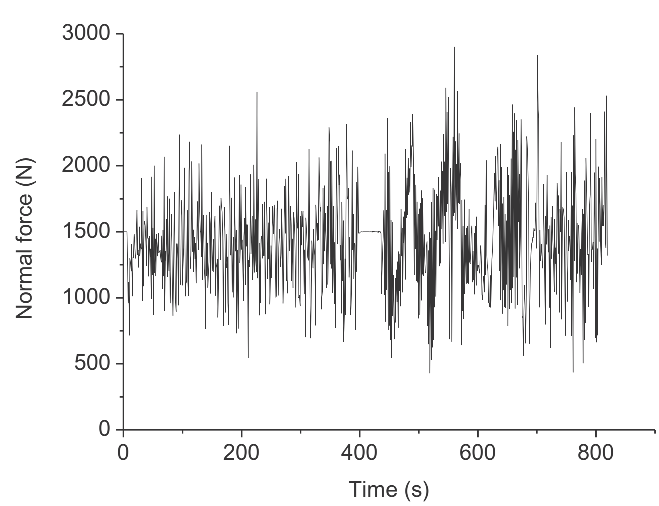

Fig. 4. Time domain feature of the normal force acting on the cutterhead. The test is performed on an intact rock block with a normal force of 1.5 kN.

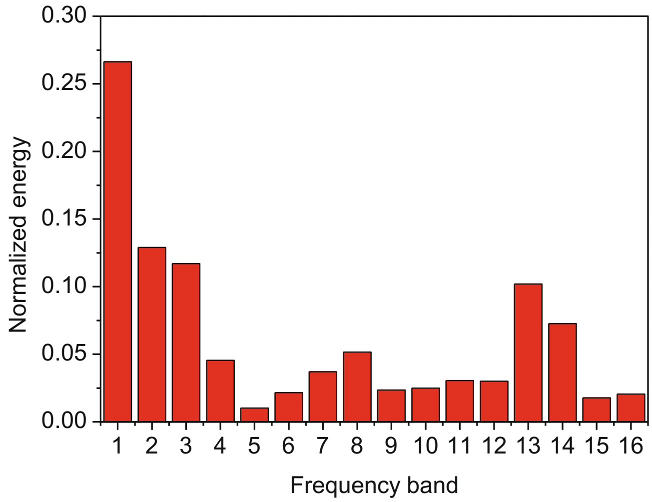

Fig. 5. Normalized wavelet energy spectrum for intact rock block at 15 min. The normal force acting on rock block is 1.5 kN.

Table 3
Expressions and calculated results of 11 time domain feature parameters of the normal force. Time domain feature parameters of band 14 for an intact rock block, with a normal force of 1.5 kN, are presented as an example in this table.

Parameter	Expression	Calculated result
Mean	$x_{\mathrm{m}} = \frac{\sum_{n-1}^{N} x_n}{N}$	0.96
Peak	$x_{\mathrm{p}} = \max\lvert x_n \rvert$	4.00
Root amplitude	$x_{\mathrm{ra}} = \left[\frac{\sum_{n=1}^{N}\sqrt{x(n)}}{N}\right]^2$	0.50
Root mean square	$x_{\mathrm{rms}} = \sqrt{\frac{\sum_{n=1}^{N}[x(n)]^2}{N}}$	1.47
Standard deviation	$x_{\mathrm{std}} = \sqrt{\frac{\sum_{n=1}^{N}[x(n)-x_{\mathrm{m}}]^2}{N-1}}$	1.11
Skewness	$x_{\mathrm{ske}} = \frac{\sum_{n=1}^{N}[x(n)-x_{\mathrm{m}}]^3}{(N-1)x_{\mathrm{std}}^3}$	1.12
Kurtosis	$x_{\mathrm{k}} = \frac{\sum_{n=1}^{N}[x(n)-x_{\mathrm{m}}]^4}{(N-1)x_{\mathrm{std}}^4}$	3.47
Crest	$x_{\mathrm{c}} = \frac{x_{\mathrm{p}}}{x_{\mathrm{rms}}}$	2.72
Margin	$x_{\mathrm{ma}} = \frac{x_{\mathrm{p}}}{x_{\mathrm{ra}}}$	7.97
Shape	$x_{\mathrm{sha}} = \frac{x_{\mathrm{rms}}}{x_m}$	1.53
Impulse factor	$x_{\mathrm{i}} = \frac{x_{\mathrm{p}}}{x_{\mathrm{m}}}$	4.17

(x_{ske}), kurtosis (x_{k}), crest (x_{c}), margin (x_{ma}), shape (x_{sha}), and impulse factor (x_{i}). For example, for the intact rock cutting with normal forces of 1.50 kN, the 11 time-dominant feature parameters of frequency band 14 are listed in Table 3.

3.2.3 Correlation analysis

Through the WP transform, energy and time domain feature parameters of each frequency band and energy entropy can be obtained. For improving the accuracy of the reliability assessment and avoiding the problem of dimensionality, it was necessary to select salient feature parameters indicative of the tool wear state from the feature set, including feature band energy, energy entropy, and time domain feature parameters of feature bands.

In this section, correlation analysis is employed to calculate the correlation coefficients (CCs) between band energy, energy entropy, time domain feature parameters, and wear values of disc cutters. Feature parameters with high CCs were selected as the salient features to assess the reliability of cutters. The formula expressing the correlation coefficient between $x(n)$ and $y(n)$ is

$$C_{xy} = \frac{\sum_{n=0}^{\infty} x(n)y(n)}{\left[\sum_{n=0}^{\infty} x^2(n)\sum_{n=0}^{\infty} y^2(n)\right]^{\frac{1}{2}}}, \tag{8}$$

where C_{xy} is the correlation coefficient, $x(n)$ and $y(n)$ represent feature parameters and wear values of disc cutters, respectively.

For intact rock with a normal force of 1.5 kN, CCs between band 16 energy, energy entropy, and wear loss were calculated, as shown in Fig. 6. It was observed that the CC of band 14 energy was 0.89, which was larger than that of other feature parameters. Thus, band 14 was selected as the feature band, in which the band energy, energy entropy, and time domain feature parameters are most related with wear. Furthermore, it can be inferred

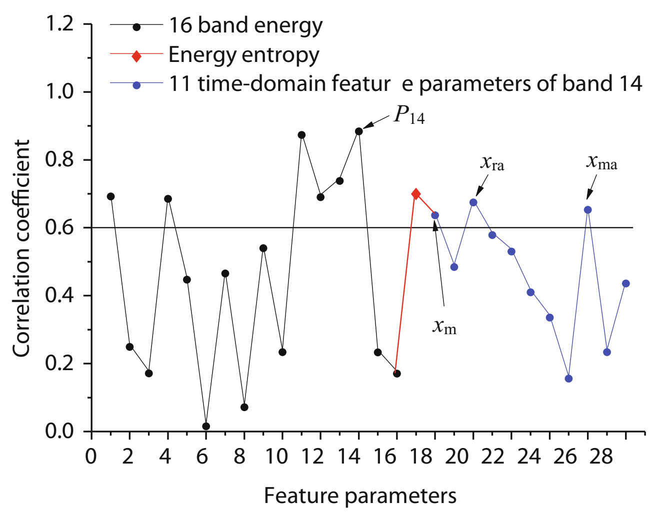

Fig. 6. Correlation coefficients between band energy, energy entropy, and time domain feature parameters of band 14 and cutter wear. The test is performed on an intact rock block with a normal force of 1.5 kN.

that time domain feature parameters of the feature band are more sensitive to wear loss than that of other frequency bands. Therefore, the 11 time domain feature parameters of band 14 were calculated, as illustrated in Fig. 6. The calculated results show that the CCs of the 1st, 3rd, and 9th time domain feature parameters, corresponding to x_{m}, x_{ra}, and x_{ma}, of band 14 were greater than 0.6. With reference to the research conducted by Chen et al. (2011), the feature band energy P_{14}, x_{m}, x_{ra}, and x_{ma} were extracted as the salient feature parameters. As a result, the input feature vector of the logistic regression model was $\boldsymbol{X} = (P_{14}, x_m, x_{\mathrm{ra}}, x_{\mathrm{ma}})$.

3.3 Logistic regression

After determining the feature vector $\boldsymbol{X}$, the reliability of the disc cutter can be obtained by establishing logistic

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regression models. The logistic regression equation is expressed as:

$$y = a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4, \tag{9}$$

where a_1, a_2, a_3, and a_4 are salient feature parameters, x_1, x_2, x_3, and x_4 represent the salient features, and y is the reliability of the cutters. For intact rock blocks with a different normal force, a_1, a_2, a_3, and a_4 represent P_{14}, x_m, x_{ra}, and x_{ma}, respectively. Logistic regression equations for different groups of tests are listed in Table 4.

4 Results and discussion

4.1 Influence of dip angle on the reliability of disc cutters

Jointed rock mass is commonly encountered while TBMs advance in a tunnel. Previous studies have indicated that TBM performance significantly varies with variation in the dip angle (Hamidi, Shahriar, Rezai, & Rostami, 2010; Yagiz, 2008). Consequently, wear loss and reliability of disc cutters may be affected. To analyze the influence of dip angle on the reliability of disc cutters, rolling cutting tests were conducted on jointed rock blocks with dip angles of 0°, 30°, 45°, 60°, and 90° and joint spacing of 20 mm.

Figure 7 shows the relationships between the reliability of disc cutters, wear loss, and dip angles. According to the experimental results, the wear loss of cutters reached a minimum of 8 mg for a dip angle of 30°. Calculated results, obtained from the logistic regression model, indicated that the reliability of disc cutters was stable as the dip angle ranged from 0° to 60°. However, when the dip angle increased to 90°, the reliability sharply decreased.

This phenomenon suggests that the dip angle is one of primary factors that influence the wear of cutters in jointed rock mass. Consequently, the reliability of disc cutters was affected. As stated by Gong, Zhao, and Jiao (2005), the rock chipping angle, which represents the angle between the tunnel face and rock damage plane, increases as the dip angle decreases. In this study, the rock chipping angle reached a maximum value when the dip angle was 30°. Creaks initiate from the joint plane and propagate upward to the surface of rock block, along the shortest propagation path. The wear value of cutters reached a minimum in this case. When the dip angle increased to 90°, wear loss exceeded the threshold, leading to the evident reduction in reliability. Comprehensive consideration suggests that the optimal dip angle for disc cutters is 30°. In engineering practice, it is necessary to select an appropriate angle between the cutterhead and joint plane, to improve the TBM cutting efficiency and the useful life of cutters. This conclusion is in agreement with the numerical simulation result from the study conducted by Gong et al. (2005), which investigated the influence of dip angle on rock fragmentation. In this study, the penetration rate of the TBM reached a maximum when the dip angle was 30°, i.e., the cutting efficiency of the TBM reached a maximum at this angle.

A comparison between the experimental and theoretical results is made to highlight the effect of the dip angle on the reliability of the disc cutter. Generally, disc cutters wear out uniformly. Rabinowicz (1965) derived the formula for wear loss, according to the abrasive wear mechanism, which is expressed as

$$V = K_s \frac{F_N}{H} l, \tag{10}$$

where V is the wear volume of tools, K_s represents the wear coefficient (which is related to the strength of the cutters, $K_s = 24 \times 10^{-3}$), F_N denotes the normal force acting on the cutters, H is the hardness of the worn surface, and l is the sliding distance. On the basis of the study conducted by Wang, Li, Zhao, and Zhang (2017), l can be calculated by

$$l = \xi L = 0.00528 \left(\frac{F_R}{F_N}\right)^{1.2} p^{0.5}, \tag{11}$$

where ξ is the slip ratio, L is the rolling distance, F_R represents the rolling force acting on the disc cutter, and p is the penetration depth.

The calculated results are presented in Fig. 7. By comparison, it was observed that the calculated wear loss and reliability varied slightly with the variation of dip angle, i.e., Eqs. (10) and (11) ignore the effect of dip angle on wear loss. Despite this, the calculated reliability was similar to the experimental results, as the dip angle ranged from 0° to 60° the maximum difference between the experimental and theoretical results in this range was 7.48%. Thus, Rabinowicz's formula can be applied when estimating the reliability for a dip angle less than 60°. However, in other cases, the calculated results may not coincide with the experimental results.

4.2 Comparison of reliabilities in mixed-face and single ground conditions

In addition to jointed rock mass, mixed-face ground is also frequently encountered in practice, owing to the complexity of geological conditions. Potential hazards in this type of ground include abnormal cutter wear, ground loss, clogging, and blow-outs (Ma, Yin, Gong, & Wang, 2015; Shirlaw, 2016), which may significantly influence the remaining useful life of disc cutters. For this problem, a comparison of reliabilities of disc cutters, in mixed-face and single ground conditions, and the influencing factors were analyzed. In this section, rock blocks with different interlayers were prepared to model mixed-face ground; intact rock block represents single ground.

To quantitatively study the reliability of cutters, we propose a term of specific strength (S_{str}), which is defined as the ratio of the uniaxial compressive strength (UCS) between interlayers and the main rock. Considering that abnormal wear may occur under mixed-face ground conditions, the specific energy (S_E) in single and mixed-face ground conditions was calculated to assess the difficulty

Table 4
Logistic regression equations for each group of tests.

Groups	Logistic regression equation
Rock blocks with different dip angles	$y = 21.43x_1 + 199.99x_2 + 0.40x_3 - 0.22x_4$
Rock blocks with different interlayers	$y = 2.37x_1 - 9.50x_2 + 0.68x_3$
Intact rock blocks with different trusts	$y = 1.13x_1 + 10.50x_2 - 15.17x_3 - 0.04x_4$
Rock blocks with different rotational speeds	$y = 0.49x_1 + 0.07x_2 - 0.26x_3 + 0.28x_4$

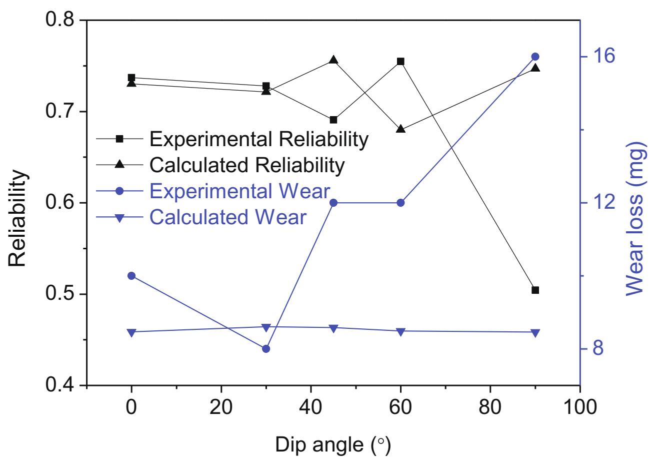

Fig. 7. Variations of the reliability and wear loss of disc cutters with dip angle. The reliability and wear loss are obtained from the experiment and Rabinowicz's formula, respectively.

of rock breakage. S_E is the energy required to break a unit volume of rock mass during TBM tunneling (Teale, 1965). A smaller specific energy indicates a lower difficulty of TBM advancement. The formulae of S_{str} and S_E are expressed as follows:

$$S_{str} = \frac{\sigma_I}{\sigma_R}, \tag{12}$$

$$S_E = \frac{W}{V} = \frac{F_N p + F_R l}{V}, \tag{13}$$

where S_{str} denotes specific strength, σ_I is the UCS of the interlayers, σ_R represents the UCS of the main rock, F_N and F_R represent the normal and rolling forces, respectively, p is the penetration depth, l denotes the rolling distance, and V refers to the volume of rock chips.

Figure 8(a) illustrates the variations in the reliability and wear loss of disc cutters with S_{str}. For rock blocks with soft, medium hard, and hard interlayers, and an intact rock block, S_{str} was equal to 0.12, 0.14, 0.92, and 1, respectively. When disc cutters rolled in mixed-face grounds, the reliability of the cutters increased slightly from 0.7319 to 0.7321, with an increase in the strength of the interlayers. However, in single ground, the value dropped sharply to 0.6909. However, the wear loss continuously increased with an increment in S_{str}. It is important to note that wear for a jointed rock mass is approximately 4.45 times larger than that for a rock block with hard interlayers. This indicates that the reliability does no show a clear correlation to wear loss in mixed-face ground. To better understand the factors

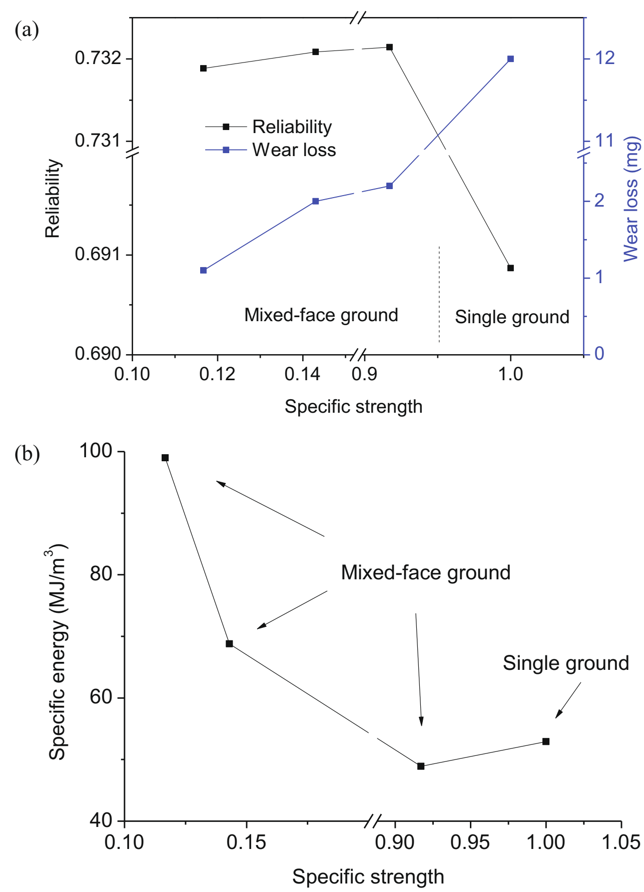

Fig. 8. Curves representing reliability vs. (a) wear loss and (b) specific energy in mixed-face and single grounds. The interlayer includes hard, medium hard, and soft interlayers.

influencing the reliability of disc cutters, S_E in different ground conditions was obtained, as depicted in Fig. 8(b). It was observed that in mixed-face ground, S_{str} sharply decreased with an increase in S_E. In single ground, however, S_{str} slightly increased.

From the variations in reliability, wear loss, and S_E, it can be concluded that the factors that influence reliability in mixed-face and single ground, are different. Specifically, the difficulty of TBM excavation contributes more to the reliability of disc cutters in mixed-face ground, however, in single ground, the effect of wear loss is more influential.

As a result of the difference in strength between the main rock and interlayers, it was observed that disc cutters frequently fall into interlayers during the experiment, causing the discontinuance of cutter rotation. Therefore, the torque required to penetrate the ground increased and the cutterhead vibrated drastically. Moreover, the soft interlayer cannot provide sufficient rolling force for the disc cutters to overcome the pre-torque exerted by the cutterhead, causing the flat wear of cutters (Zhao, Gong, & Eisensten, 2007), as presented in Fig. 9(a). The phenomenon frequently occurs in tests performed on rock blocks with soft and medium hard interlayers. As the strength of the interlayers increased, the discontinuation of the cutterhead and flat wear progressively disappear, and it became easier for the TBM to bore the ground. Thus, S_E decreased and the reliability of cutters increased. Additionally, in the experiment, tests on rock blocks with soft, medium hard, and hard interlayers, and intact rock occur for approximately 2, 5, 6, and 13 min, respectively. Therefore, the wear loss of disc cutters showed a positive correlation with S_S in mixed-face ground. However, in single ground, the cutter wear was characterized by normal wear, as illustrated in Fig. 9(b). In the test conducted on intact rock, disc cutters roll smoothly on the rock surface, consequently, wear loss sharply increased. When the value was more than the threshold in the logistic regression model, the reliability of cutters decreased.

4.3 Influence of normal force on reliability of disc cutters

The normal force exerted by the cutterhead is one of the crucial operational parameters for TBM. To obtain high cutting efficiency during tunneling, in different geological conditions, the normal force may be adjusted, whenever necessary. To eliminate the effect of joints, intact rock blocks were prepared for the experiment, to study the influence of normal force on reliability. The normal force acting on the cutterhead was set to 1.00, 1.25, 1.50, 1.75, and 2.00 kN, respectively.

As shown in the experimental results (Fig. 10), the wear loss of disc cutters exhibited a positive correlation with the normal force. The reliability reached 0.73 when the normal force was less than 1.25 kN. However, further increase in the normal force caused the reliability to sharply reduce. For a normal force of 1.50 kN, the reliability was 0.52, which was 28.77% less than that for a normal force of 1.25 kN. As the normal force increased higher than 1.5 kN, the reliability was slightly reduced.

This phenomenon suggests that the reliability of cutters is primarily affected by wear for different normal forces. In tunnel engineering, cutters are primarily damaged by abrasive wear. Under the action of a normal force, hard particles in the rock will pierce into the cutter ring. As cutters roll on the tunnel face, materials can be simultaneously removed from the cutter ring, owing to the lower hardness level, which causes micro cutting, scratches, grooves, and ploughing on the worn surface. The increase in the normal force aggravated the mass of remover materials; therefore, wear loss increased. As the wear loss exceeded the threshold, the cutters ceased to work and the reliability sharply decreased. In addition, wear loss under different normal forces was calculated by Eqs. (10) and (11). The calculated reliability is presented in Fig. 10. It can be observed that the calculated results are in good agreement with those of the experiment. Therefore, Rabinowicz's and Wang's models are suitable for estimating cutter wear and reliability in intact rock block.

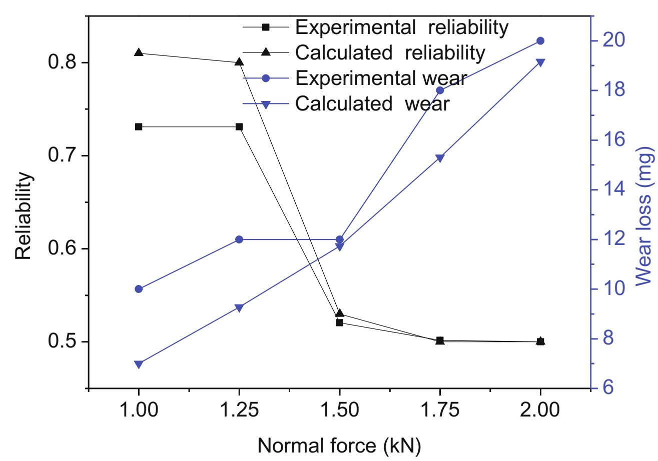

Fig. 10. Variations of reliability and wear loss of disc cutters with the normal force. Reliability and wear loss are obtained from the experiment and Rabinowicz's formula, respectively. Tests are performed on intact rock block and the normal force is applied on the cutterhead in advance.

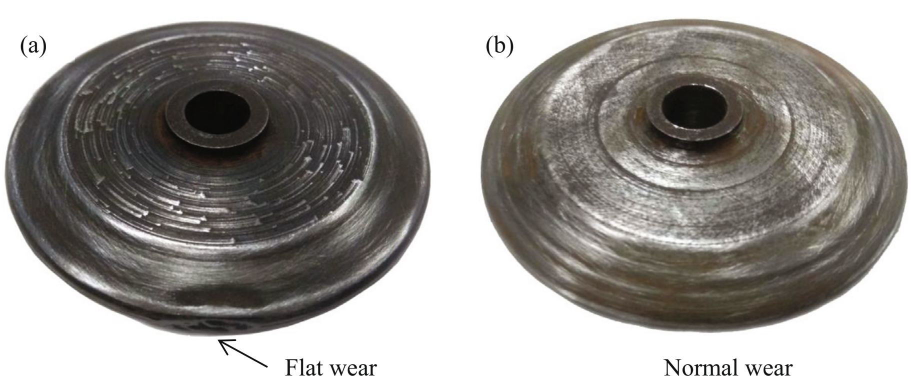

Fig. 9. Wear of disc cutter in (a) mixed-face ground and (b) single ground.

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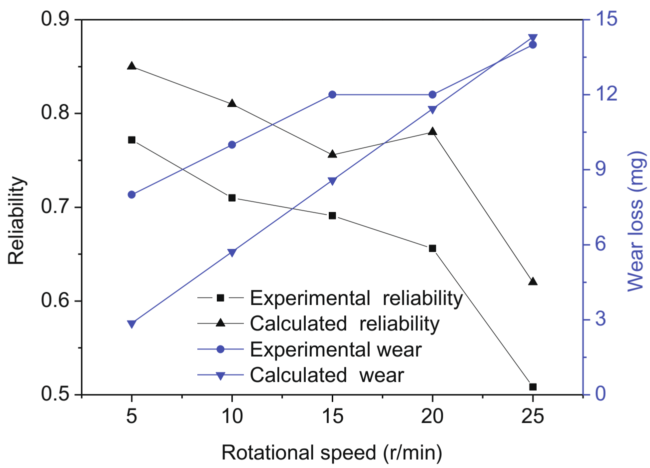

Fig. 11. Relationships between reliability, wear loss of disc cutters, and rotational speed. Reliability and wear loss are obtained from the experiment and Rabinowicz's formula, respectively. Tests are performed on jointed rock block with a dip angle of 45° and joint spacing of 20 mm.

4.4 Reliability of disc cutter for different rotational speeds

Owing to the different installation radius of disc cutters on the cutterhead, the sliding speed of cutters varies from 2.3 to 2.9 m/s for gauge cutters, and from 1.4 to 1.7 m/s for the average cutter position in actual TBMs (Macias et al., 2016). To assess the reliability of cutters in different positions, the rotational speed of the miniature cutterhead was set to 5, 10, 15, 20, and 25 r/min in the experiment. Tests were conducted on jointed rock block, with a dip angle of 45° and a joint spacing of 20 mm. The duration of each test was approximately 10 min.

Figure 11 illustrates the variations of reliability and wear loss of the disc cutter with rotational speed. Based on the experimental results, the relationship between wear loss and rotational speed was observed to be approximately proportional. Therefore, the experimentally obtained reliability progressively reduced with an increase in rotational speed, i.e., rotational speed of the cutterhead can also influence the reliability of cutters by abrasive wear. The sliding distance of cutters is proportional to rotational speed. A larger sliding distance can cause a larger amount of materials to be removed from the cutter ring (Frenzel, Kasling, & Thuro, 2008). Thus, wear loss increased continually with an increase in rotational speed. Additionally, the high rotational speed of the cutterhead will cause the cutters to drastically vibrate, which can also aggravate cutter wear. Eventually, the reliability of the cutters will reduce. Experimental results are in agreement with engineering practices, in which the number of exchanged disc cutters increased from the center to the outer edge of the cutterhead (Hassanpour et al., 2014). Therefore, to avoid time delays and budget overruns, wear resistance of gauge cutters should be higher than that of cutters installed in other positions.

The experimental results were also compared to Rabinowicz's prediction model, as shown in Fig. 11. It was observed that the trends of the calculated results were similar to that of experimental results. However, there was a clear difference between the calculated and experimental reliabilities, especially when the rotational speed was 20 r/min; the calculated reliability was 20.00% greater than that obtained from the experiment. This may be because Rabinowicz's model ignores the influence of the joint on wear loss. Therefore, Eq. (10) overestimates the reliability of the cutters. However, the equation can be employed to estimate the trends of reliability for different rotational speeds.

5 Conclusions

The rolling cutting tests were conducted to simulate the TBM cutting process under different geological and operational conditions. Subsequently, a novel reliability estimation method, based on a logistic regression model, was introduced. The influence of dip angle, strata, normal force, and rotational speed on the reliability of the disc cutter were discussed.

As shown in the test results, the reliability of disc cutters showed stability for a dip angle of less than 60°; a dip angle of 30° was most beneficial to the TBM excavation. In mixed-face ground, owing to the discontinuations of the cutterhead and flat wear of the disc cutters, the reliability of disc cutters was primarily affected by the difficulty of TBM excavation. An increase in S_S was conducive to the increase in reliability. However, in single ground, wear loss contributed more to the reliability of disc cutters. Additionally, wear loss of cutters monotonically increased with increasing operational parameters (i.e., normal force and rotational speed). Operational parameters of the TBM can reduce the reliability of cutters through increasing abrasive wear loss.

Although we attempted to realistically simulate the rock breaking process by TBM cutters, the difference between laboratory tests and engineering practice cannot be ignored. The obtained results only provide some references for the design of operational parameters and scheme of tunnel lines. In this experiment, it was difficult to observe the process of crack initiation and propagation within the rock block; therefore, the rock cutting mechanism remains unclear. Further experiments could, therefore, be conducted on transparent materials, such as Plexiglas, to overcome this limitation.

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Declaration of Competing Interest

The authors declare that they have no conflict of interest. No financial and personal relationships with other people or organizations that can inappropriately influence our work. There is no professional or other personal interest that could be construed as influencing the review of this manuscript.

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